X-731-65-416

METEOROLOGICAL EXPERIMENT USING THE OMEGA SYSTEM FOR POSITION LOCATION

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SPACECRAFT: APPLICATION TECHNOLOGICAL SATELLITE ATS-C

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1. SUMMARY

An Omega Position Location Equipment (OPLE) experiment is proposed which combines the Omega Navigation System, recently developed by the U. S. Navy, with existing satellite technology for the purpose of establishing a basis for the design of a world-wide meteorological platform location and data collection system. This experiment is designed to demonstrate that the position of a large number of free-floating meteorological platforms dispersed over the earth can be located, and that weather data can be collected from them synoptically or quasi-synoptically. The simplicity of the Omega System provides confidence that the weight and safety limitations imposed by the Federal Aviation Agency on constant-level balloons can be satisfied.

This proposed experiment is based on the overall operational considerations discussed in section 4 and is not designed to explore the full range of possible applications but rather to prove the feasibility of the basic concepts. However, the proposed experiment provides for expansion of the basic ideas into a highly versatile world-wide system of major importance to the ever increasing needs of meteorologists and oceanographers. In addition, future expansion could include the location and collection of data from super-sonic aircraft, as well as other moving vehicles, to provide a significant contribution to the growing air traffic control problem.

2. INTRODUCTION

The proposed experiment unites proven satellite technology with the world-wide Omega Navigation System which has been demonstrated and is presently being implemented under the U. S. Navy's Omega Project. The simplicity of the Omega concept provides confidence that the goals of this proposal will be attained and that the technology necessary to develop a complete Omega Position Location Equipment (OPLE) system exists.

A basic description of the Omega System is given in section 3, while a detailed analysis is contained in reference (1). Functional concepts of an operational world-wide platform location and data collection system based on the Omega network are given in section 4. An experiment designed to prove the feasibility and to explore the potentials of such an operational system is contained in section 5.

The concepts described in the following sections are based on the use of a synchronous satellite, although the basic ideas are adaptable to both synchronous and low-orbiting satellites. An operational OPLE system based on these concepts would be compatible with both free-floating buoys and balloons as well as with fixed stations and would provide a substantial contribution to the World Weather System (WWS). A high degree of flexibility is possible in the development of the system depending on operational choices and needs. Because of the potential national and international impact of such a system, the work being done under the Weather Bureau's WWS program and by the World Meteorological Organization (WMO) will be closely monitored so that the equipments and techniques developed during this experiment will be compatible with criteria established by these organizations.

3. OMEGA SYSTEM DESCRIPTION

The Omega System was developed at the Naval Electronics Laboratory with assistance from several other organizations including the Harvard Cruft Laboratory and the Naval Research Laboratory. Evolution of the Omega system followed an extensive investigation of very-low-frequency propagation characteristics throughout the last decade. One result of these investigations has been to show that the 10 kc region of the VLF spectrum has a very low attenuation rate and exhibits exceptional phase stability. These characteristics permit world wide propagation of radio waves and allow phase measurements with an rms variation of less than five microseconds. Within this frequency range, the radiated energy is propagated as a guided wave in the space between the earth and the reflecting ionosphere with an attenuation rate of nearly that due to inverse spreading loss.

Near the transmitter the ground wave predominates and interference between the ground wave and the single-mode guided wave transmission causes phase shifts of considerable magnitude. Beyond a few hundred miles, the single-mode propagation dominates and the signal can be used for position measurements up to a distance of at least 5000 miles from the transmitter. Frequencies between 10 and 14 kc were chosen for use by Omega because of the high excitation of the first mode and the low higher mode interference effects at sunrise and sunset.

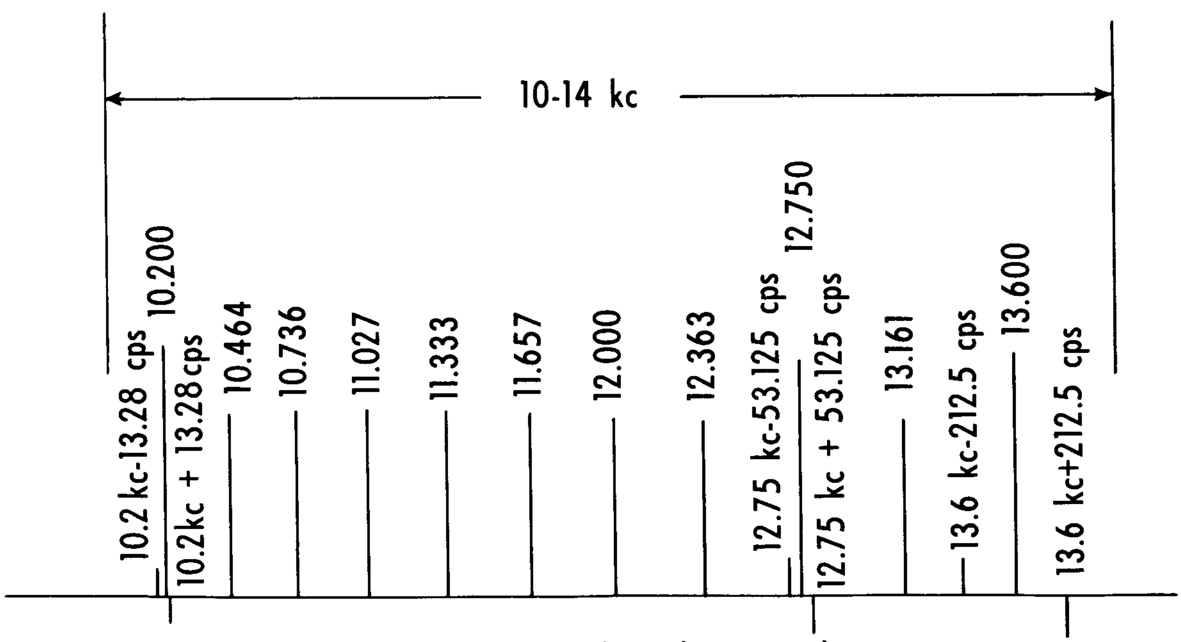
The optimization of the Omega frequencies with respect to the above medium characteristics has been verified by experimental results. The experimental phase of the Omega program is essentially completed and an overall operational design of considerable flexibility has been established and is rapidly being implemented. An Omega Project Office under the Chief of Navy Materiel, has been established to direct the construction of the entire Omega network. Three complete operational stations providing coverage over the north-western quadrant of the earth are under construction and will be used for fleet evaluation tests early in 1966. An additional five operational stations are expected to complete the Omega network by 1969.

The operational Omega system will use eight VLF transmitting stations radiating 10 kilowatts of power each with an average separation between stations of about 5000 nautical miles. It is expected that all eight transmissions will be receivable at nearly every point on earth and that at least five of the eight will produce usable signals with only a short monopole receiving antenna. The Omega receiver measures the relative phase of the signals from at least two pairs of stations - that is, three transmitters. Two lines of position (isophase contours) are generated by the phase difference between each of the two transmitter pairs and the position of the receiver is established by the intersection of the two isophase hyperbolic contours. The very long base lines between stations results in position lines that diverge only slightly and that cross each other at nearly right angles. This geometric excellence, along with the high degree of phase stability and low attenuation rates of VLF radio signals, results in a reliable system with high absolute accuracy that varies little with geographical position.

The uncertainty in an Omega line of position can be summarized as one standard deviation of about three-tenths of a mile over a daytime propagation path and about twice that at night. By the time the Omega network becomes operational, it is expected that the rms fix error, for all causes combined, will be about one mile in the daytime and two miles at night (see reference (2)). In recent tests performed by the Naval Research Laboratory, the rendezvous or station keeping accuracies attained were around 200 yards (see reference (3)). Thus, a fixed station can provide very accurate relative position measurements (and velocity measurements through continual tracking) of balloons in a large vicinity.

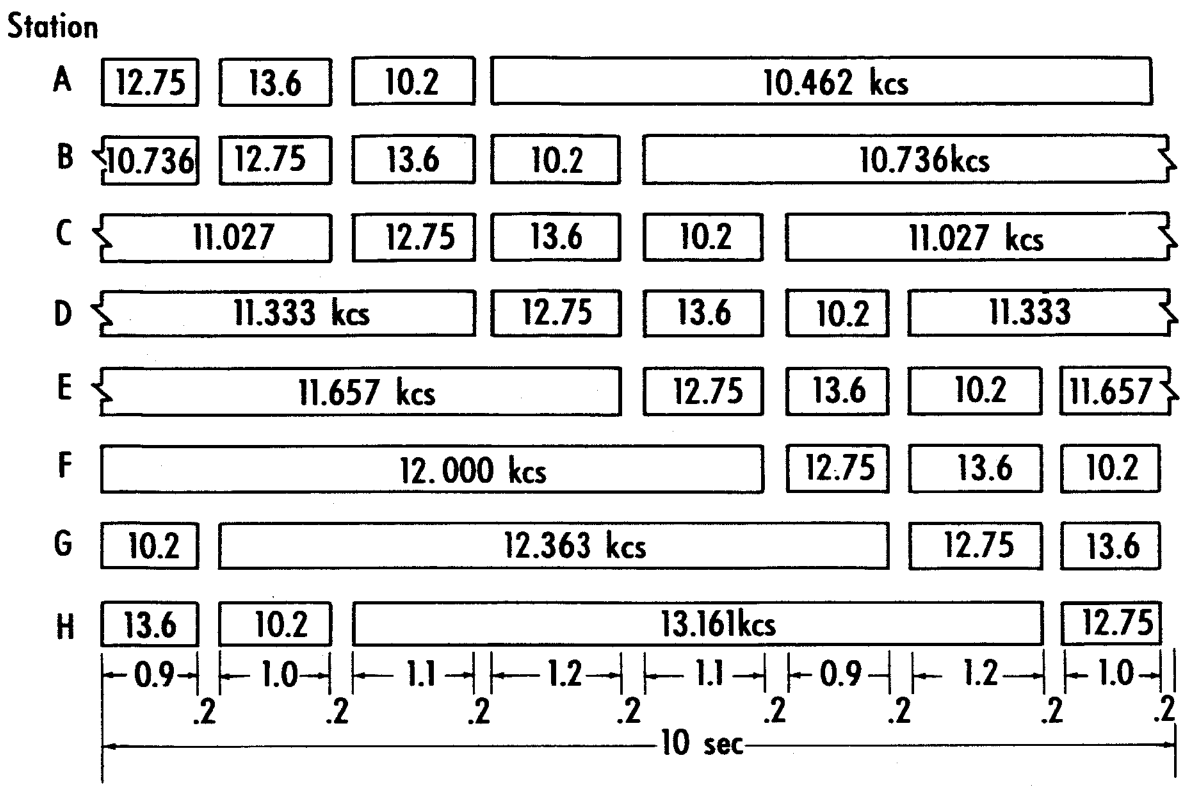
The Omega system presently being implemented provides for considerable flexibility and future expansion. The transmitted signal spectrum is shown in Figure 1 while the transmitting station time multiplexing scheme is shown in Figure 2. The primary transmission frequencies are 10.2 kc, 12.75 kc, and 13.6 kc each of which is phase modulated by a single tone of 13.28 cps, 53.125 cps and 212.5 cps tones, respectively. In addition, eight other frequencies are shown which are all sub-harmonics of 408 kc. Each of these eight frequencies is assigned to one of the eight transmitting stations in accordance with the time multiplexing diagram in Figure 2. These eight frequencies permit transmitter station identification but they are not essential to the position location function. By means of very low phase deviation, these frequencies also provide for inter-station communications for control and synchronization purposes.

Ambiguity resolution is performed by successive measurements of the received phase of the carrier difference and modulation frequencies. The carrier frequencies and their modulating tones have been selected to permit construction of the difference frequencies listed in Table 1 along with the resulting ambiguity resolution steps. No dead reckoning, lane counting or log keeping is necessary and the transmitted sequence will permit completely automatic operation on an "as required" basis.



Note: The 11.333 kc carrier may replace the 12.75 kc carrier.

Figure 1–Omega System Signal Spectrum



Note : The 11.333kc transmissions may be inter-changed with 12.75 kc.

Figure 2—Omega Transmitted Signal Format

Table 1

Omega Ambiguity Resolution Steps.

Frequency	Period	λ/2 km	λ/2 n. miles	λ/2 s. miles
10.2 kcs	98 μs	14.7	7.94	9.12
3.4 kcs	306 μs	44.1	23.8	27.4
850 kcs	1.18 ms	176.5	95.3	109.4
*1.13 kcs	880 μs	132.1	71.5	82.0
212.5 cs	4.72 ms	722	382	438
53.125 cs	18.85 ms	2830	1525	1750
13.28 cs	75.4 ms	11,300	6100	7000

*Proposed replacement of the 850 cps tone.

4. OPERATIONAL OMEGA POSITION LOCATION AND METEOROLOGICAL DATA COLLECTION SYSTEM CONCEPTS

4.1 Functional Description

When the Omega system becomes operational, any vehicle will be able to locate its position with only appropriate VLF receiving equipment, suitable processing and display equipment, and a navigator equipped with necessary charts, instructions and procedural information. If all of the above mentioned items, except for the VLF receiving equipment, could be at a convenient central processing location, and if an adequate communication circuit could be provided between the VLF receiver on the vessel and the central processing equipments, then the position of the vessel could be ascertained at the central processing location and the size of the equipment aboard the vessel could be reduced accordingly.

In line with these thoughts, it seems reasonable to consider the possibility of electrically connecting the platform VLF receiver to the central processing location through a synchronous satellite repeater.

In this way, both the platform and the satellite would essentially become transponders although different frequency conversion and stabilization schemes would be used for each. A frequency drift cancellation technique would be used to eliminate the need for a highly stable frequency source on the platform. In this technique the stability of the received interrogation carrier as generated by the ground station would be used to determine the platform transmitter stability, the only error introduced by the platform being proportional to the offset frequency between the received and transmitted carriers. The platform would contain a suitable VLF receiver, meteorological sensors, multiplexing equipment and a VHF transmitter. The VHF link for each platform would be of relatively narrow bandwidth since the VLF Omega Spectrum is narrow band by necessity and the meteorological sensors would be low in data rate.

4.2 System Description

An operational system, as shown in Figure 3, would consist of, (1) an OPLE Control Center, (2) a Command and Data Acquisition Station, (3) a synchronous satellite, and (4) the OPLE platforms working in conjunction with the Omega network. The OPLE Control Center will originate all the control signals that determine the sequencing of platform addresses, and the times of interrogation. The OPLE Control Center will receive the Omega transmissions to derive timing and to determine the state of the Omega net. Satellite availability times will come from the Satellite Control Center and the OPLE Control Center will

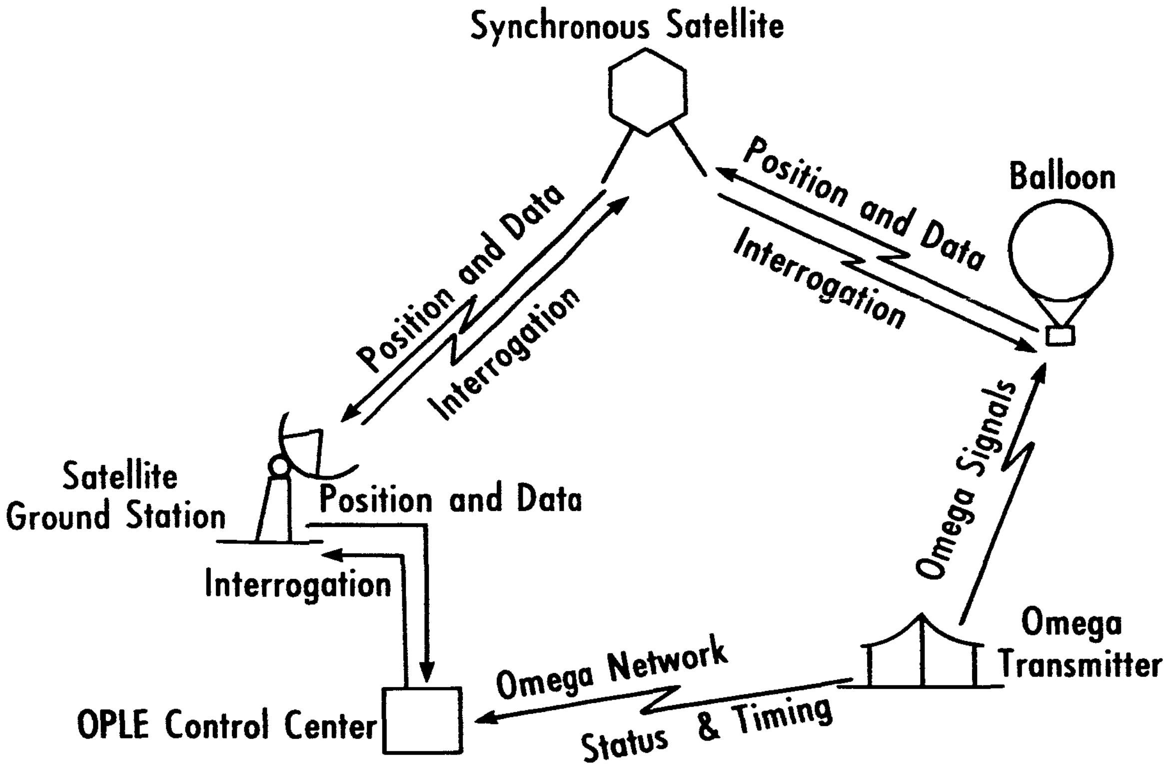


Figure 3–OPLE Network Diagram

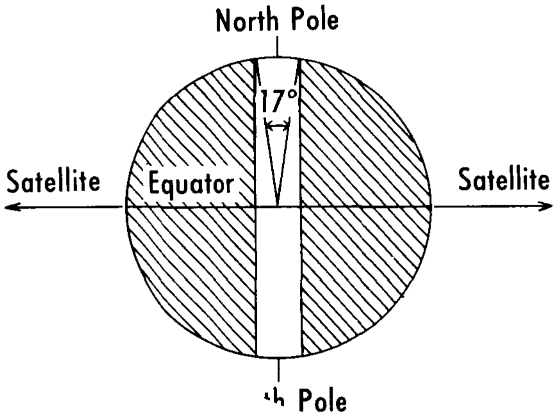
then determine which platforms are to be interrogated and the times of interrogation. This information will be sent to the Satellite Command and Data Acquisition (CDA) Station and to the interrogation transmitter.

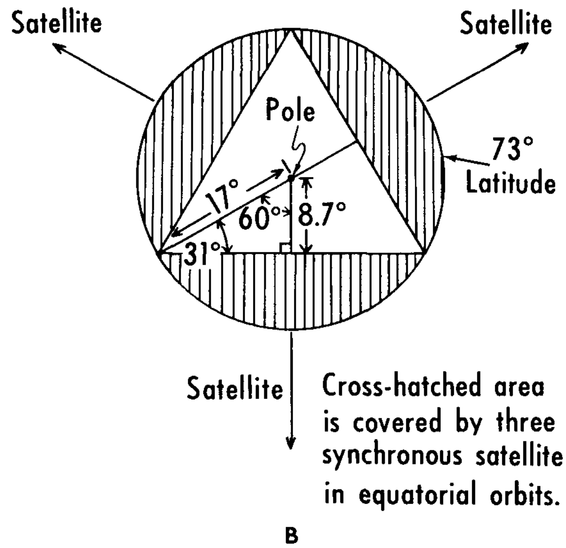
When a platform receives its address from the interrogation transmitter, it turns on a VHF transmitter, a VLF receiver, and starts a low precision timer. The incoming Omega signals are up-converted as received and relayed to the satellite along with an up-converter reference followed by data from the meteorological sensors in time sequence. The satellite again translates this signal in frequency and retransmits it to the CDA station which has previously been instructed by the satellite control center to accept the platform transmission. The CDA Station will relay this signal to a data processing center where signal-tracking and phase-measuring equipment will locate the position of the platform in much the same way as would a shipboard navigator using the conventional Omega system. The meteorological data will be processed to baseband and made available to the users.

Under the concept proposed above, the required platform-to-satellite contact time would be about three minutes and the required bandwidth would be about 2 kilocycles. Since the satellite transponder would have a much greater bandwidth capability than two kilocycles (say hundreds of kilocycles for example) it would be possible to frequency multiplex the platform transmissions to increase the number of platforms that could be serviced. That is, perhaps 50 different transmission frequencies could be divided up according to geographical areas. The fifty simultaneous interrogations, each of three minutes duration, would allow 1000 platform interrogations per hour or a total of 2000 platforms, each interrogated once every two hours or 4000 platforms, each interrogated every four hours. With three equatorial synchronous satellites, 6000 to 12,000 balloons could be serviced with world-wide coverage.

4.3 Global Coverage Considerations

The circle of illumination on the earth by an equatorial synchronous satellite has a radius of about 81 degrees of longitude at the equator. This circle is centered on the equator and extends to within about 9° of each pole. With two synchronous satellites in equatorial orbits spaced on opposite sides of the earth, the total coverage would include all but a segment circling the earth of about 17° of width as illustrated in Figure 4a. With three synchronous





Fig[illegible] by two equatorial syn- [illegible]us satellites

Figure 4b–Polar blind region for three equatorial synchronous satellites

satellites in equatorial orbits equally spaced around the earth, complete coverage is provided from about 73° north latitude to 73° south latitude all around the earth. This coverage would extend to the arctic and antarctic circles which are located at approximately 66° latitude with a platform-to-satellite angle of about 7 degrees. The spherical triangular areas located at the poles which are not covered are illustrated by Figure 4b.

The extremely poor conductivity in the arctic permafrost and polar icecap regions will result in a different velocity of propagation at VLF as compared with other areas of the earth. The extent of this difference is difficult to determine at frequencies as low as 10 kc where the depth of penetration of the ratio wave is so great. However, the difference in phase delay is dependent upon the conductivity so that in principle, it should be possible to derive correction coefficients for the polar regions in the same way as will be done for the land masses. The Omega project has been concerned with this potential problem and has established monitoring stations at College, Alaska (about 65° north latitude) and in Northern Norway (about 70° north latitude). Results to date indicate that phase disturbances are small in magnitude at least at these latitudes and should be correctable so that the main concern is to provide adequate signal strength to overcome the high attenuation in the polar regions. The location of the Omega transmitting sites have been selected with this limitation in mind. However, the possibility exists that difficulties may be experienced in the polar regions.

Polar region coverage could be provided by an additional low orbiting satellite using the Goddard Interrogation, Recording and Location System (IRLS - see reference (4)). Assuming a 600 nautical mile polar orbit, this satellite would be above the horizon at each of the poles for 17.5 percent of each orbit or about 4 hours per day. The IRL System utilizes a storage device on the satellite to store platform interrogation addresses and retrieved platform data, however, since the IRLS satellite would be in radio view of one of the synchronous satellites at all times, direct relay to the ground stations would be possible, thus producing real time data. A brief comparison of the OPLE and IRL Systems is contained in Appendix B which shows that they are not too different in performance. This comparison also tends to show that the two systems can be used in combination to provide an efficient global system.

In the event that the Omega system is capable of providing adequate coverage over the polar region, it is constructive to further discuss the possibility of global coverage with synchronous satellites. In particular, consider one synchronous satellite in an inclined plane along with two synchronous satellites in the equatorial plane. This system of satellites would provide coverage of each pole for one continuous period of time each day. The length of this time period depends on the angle of inclination of the orbital plane to the equatorial plane. A plot of the pole visibility time T in hours is given in Figure 5 for orbital inclination angles a of 0, 5 and 10 degrees.

The combination of three synchronous satellites properly phased, where one has an orbital plane inclined by 30 degrees, would allow full earth coverage over each 24 hour period. The inclined plane allows the satellite to look over the poles and view the entire area not seen by the other two satellites. Each polar area would be entirely covered for a minimum of 4 hours per day. It seems that virtually any realistic operational requirement could be met by three phased synchronous satellites, each with properly selected inclination angles.

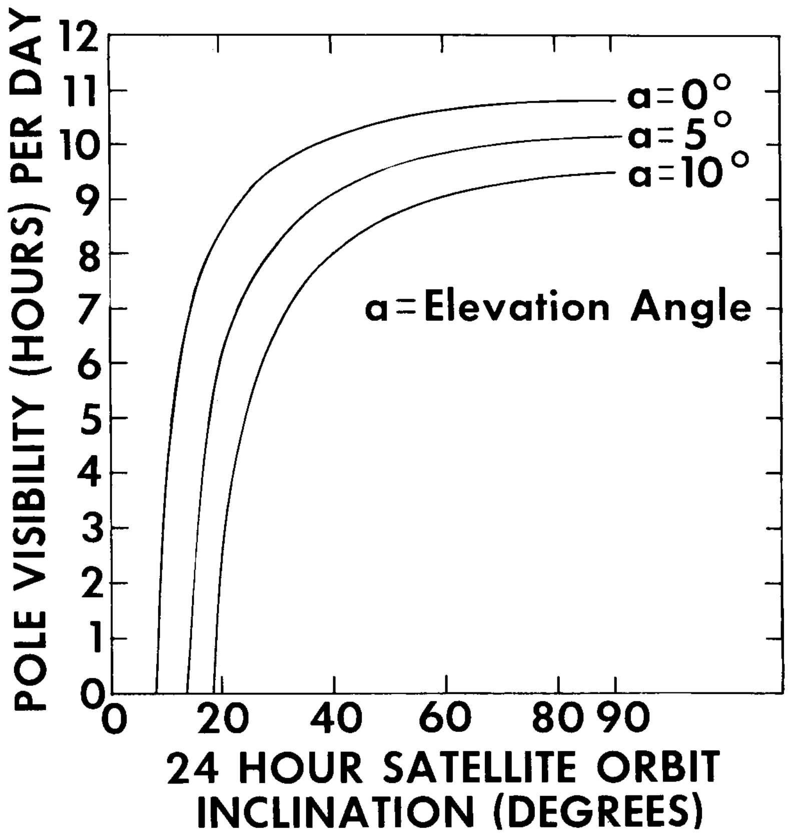


Figure 5–Synchronous satellite pole visibility time vs orbital inclination

5. EXPERIMENT DESCRIPTION

The specific experiment proposed in this section is designed only to prove the feasibility and to explore the potential of the operational system concepts discussed in the previous section. The proposed experiment consists of the following basic elements. (1) The synchronous ATS-C equipped with a linear version of the 136/148 mc ATS-B VHF transponder. While an operational system would probably operate in the 400 Mc UHF meteorological band, the time required for development of a flight qualified 400 Mc antenna/transponder system is not compatable with the ATS-C flight schedule. Also, the cost of such a development would greatly increase the cost of the overall experiment. Another benefit resulting from the choice of the 136 Mc transponder is the capability of performing other experiments with the same transponder such as will be performed on the ATS-B. (2) Twelve experimental platforms would be fabricated and deployed. The deployment plan as described later is intended to fully demonstrate the operational capabilities of the OPLE System. (3) An OPLE Control Center would be established at the Goddard Space Flight Center to determine the position of the platforms by measuring the phase of the recovered Omega signals, initiate interrogation commands, and supervise the overall operation of the experiment. (4) The CDA Station for the ATS-C will be at Rosman, N. C. and all satellite communications from and to the OPLE Control Center will be handled over land lines to this Station.

5.1 Equipment Descriptions

Platform Description. The functional and block diagrams of the platform equipment, shown in Figures 6a and 6b, consist of a common VLF/VHF antenna, a VLF receiving section, a VLF to VHF upconverting mixer, a VHF transmitter and a VHF receiver. The VLF receiving antenna requirements are modest because the received signal-to-noise ratio in the VLF band is governed by noise sources external to the receiver. It is not generally practical to build an antenna with directivity at these frequencies (nor is it desirable in this application) and the design criteria is to simply provide enough antenna aperture so that the induced atmospheric noise exceeds the receiver thermal noise. In the case of a thin monopole, this amounts to insuring that it is of sufficient length. Increasing the length increases both the induced noise and signal levels without changing their relative values. With an atmospheric noise field intensity on the order of 56 microvolts per meter per cycle of bandwidth, a two foot monopole should be of sufficient length and actual aircraft experiments performed by the Navy have shown that a two foot blade antenna is satisfactory. The VHF portion of the platform antenna will be circularly polarized and have a gain of about 3 db. In an operational system, it may be desirable to reduce this gain to permit an even broader beamwidth for closer to the horizon operation. This loss of gain can be compensated for without increasing the platform transmitter power by increasing the gain of the satellite antenna as discussed in section 6.

The VHF receiver will receive the interrogation commands and it may be on at all times or, alternatively, to conserve platform batteries it may be

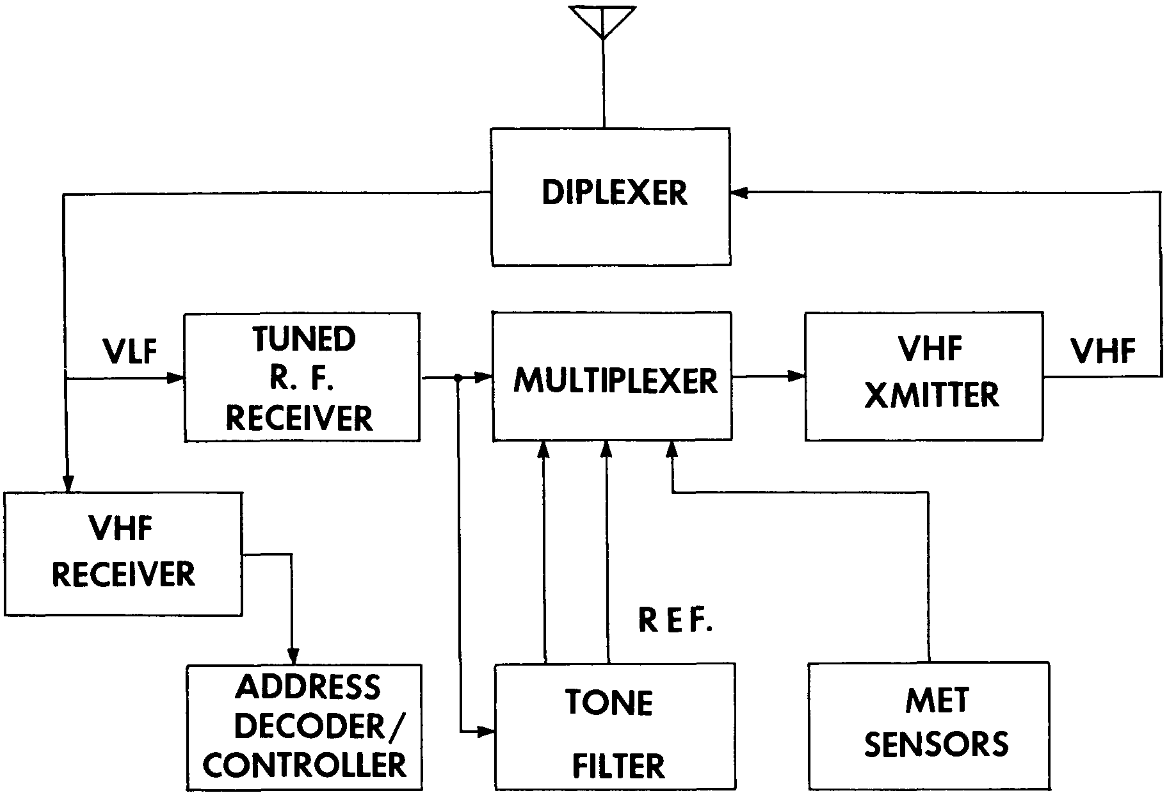


Figure 6a—OPLE Platform Functional Diagram

controlled by a periodic gross timer which can be reset to activate the receiver at some predetermined time following an interrogation. Resetting of all platform timers could also be accomplished through a master or key platform address. Upon receipt of a valid address, the remaining platform equipments will be turned on and a coarse clock will control the responding and data transmission sequence.

The received Omega signals could be up-converted and relayed to the satellite directly as received. However, more than 3.4 kc of transmission bandwidth would be required for this mode of operation. Therefore, Figure 6 shows the addition of a tone extraction filter which would serve to compress the required transmission bandwidth. The purpose of the filter is to extract the received 10.2 kc tone and translate it to a frequency position between the 12.75 kc and 13.6 kc tones. A reference tone would be added and at least one transmitting station identifying tone would be included. With the VHF antenna described in the previous paragraph, the transmitter power will be about five watts in the 2 kc transmission bandwidth. The parameters used in establishing the required power are given in Table 2. As discussed in section 6 and shown in Table 3, the

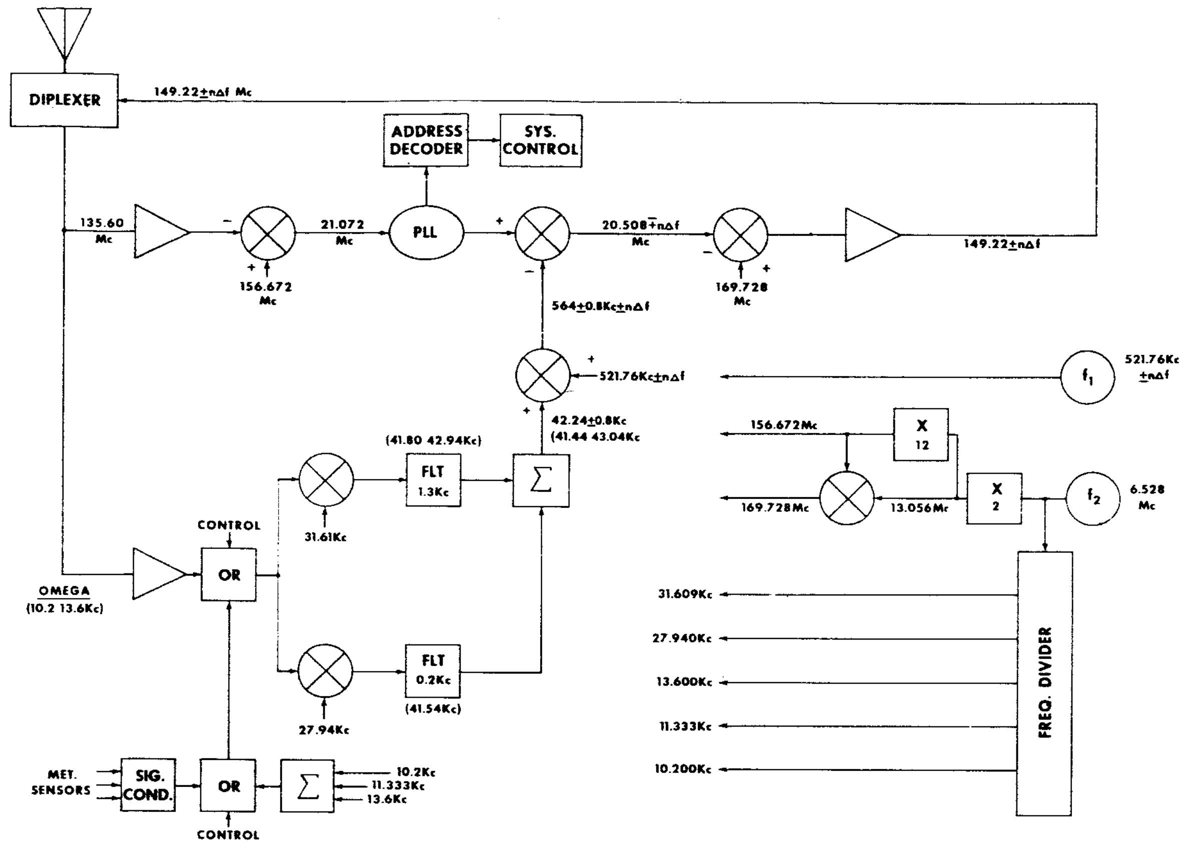


Figure 6b–OPLE Platform Block Diagram

platform transmitter power for operational platforms could be reduced to about one watt by using an optimum satellite antenna.

Transponder Description. The satellite transponder will be nearly identical to the VHF transponder flown on ATS-B. Figure 7 is a functional block diagram and Table 4 lists the transponder's major characteristics. This transponder utilizes a despun phased-array antenna to allow the antenna beam to always remain positioned on the earth thereby compensating for the stabilizing spin of the satellite. The antenna gain will be between 8.5 and 10 db but for the purposes of link calculations the 8.5 db value was used. The antenna is composed of eight elements each of which has its individual receiver, phase shifter and transmitter all coupled together with a common intermediate frequency conversion section. The satellite transponder will receive the platform transmission, convert its frequency from the 148 Mc band to the 136 Mc band, and amplify it for transmission to the CDA Station. One primary requirement of the transponder receiver is that its equivalent front-end noise spectral density be less than the

Table 2

Experiment Performance Predictions.

Platform-Satellite-Ground Station 2 kc Bandwidth Location and Data Channel			Ground Station-Satellite-Platform 2 kc Bandwidth Interrogation Channel		
Up Link 148 Mc	Nominal	Neg. Tol.	Up Link 148 mc	Nominal	Neg. Tol.
			100 watts total 8.4 watts/channel		
Transmitter Power 5 w minimum	7 dbw	0	Transmitter Power	9.2	
Platform Cable Losses	0.5	0.5	Ground Station Cable Losses	0.5	0.5
Platform Antenna Gain	3.0	3.0	Ground Station Antenna Gain	28.0	3.0
Path Losses	168.6	0	Path Losses	168.0	
Satellite Antenna Gain	8.5	1.0	Satellite Antenna Gain	8.5	1.0
Satellite Cable Losses	0.5	0.5	Satellite Cable Losses	0.5	0.5
Satellite Receiver Noise Power	165.4		Satellite Receiver Noise Power	165.4	
Received Signal-to Noise Ratio	14.3	9.3	Received Signal-to Noise Ratio	44.8	39.1
Down Link 137 Mc			Down Link 137 Mc		
25 watts total 1.7 watts/channel			25 watts total 1.7 watts/channel		
Transmitter Power	30 dbw		Transmitter Power	3.0 dbw	
Satellite Cable Losses	0.5	0.5	Satellite Cable Losses	0.5	0.5
Satellite Antenna Gain	8.5	1.0	Satellite Antenna Gain	8.5	1.0
Path Losses	168.0		Path Losses	168.0	
Ground Station Antenna Gain	28.0	3.0	Platform Antenna Gain	3.0	1.0
Ground Station Cable Losses	0.5	0.5	Platform Cable Losses	0.5	0.5
Ground Station Receiver Noise	165.4 dbw		Platform Receiver Noise	165.4 dbw	
Received Signal-to-Noise Ratio	35.9	30.9	Received Signal-to-Noise Ratio	10.9	5.9

Table 3

Operational Performance Predictions.

2 kc channel bandwidth	136-148 Mc transponder	400-450 Mc transponder
Satellite receiver noise power (1000°K)	165.4 dbw (1000°K)	-168.4 dbw (500°K)
Satellite receiver threshold level for minimal Omega distortion	+ 10.0 db	+ 10.0 db
Satellite cable and diplexer losses	1.5 db	1.5 db
Satellite antenna gain	14.0 db	14.0 db
Maximum range path losses	168.0 db	173.0 db
Platform antenna gain	0.0 db	0.0 db
Platform cable losses	0.5 db	0.5 db
Required platform transmitter power	+ 0.6 dbw (1.2 watts)	+ 2.6 dbw (1.8 watts)

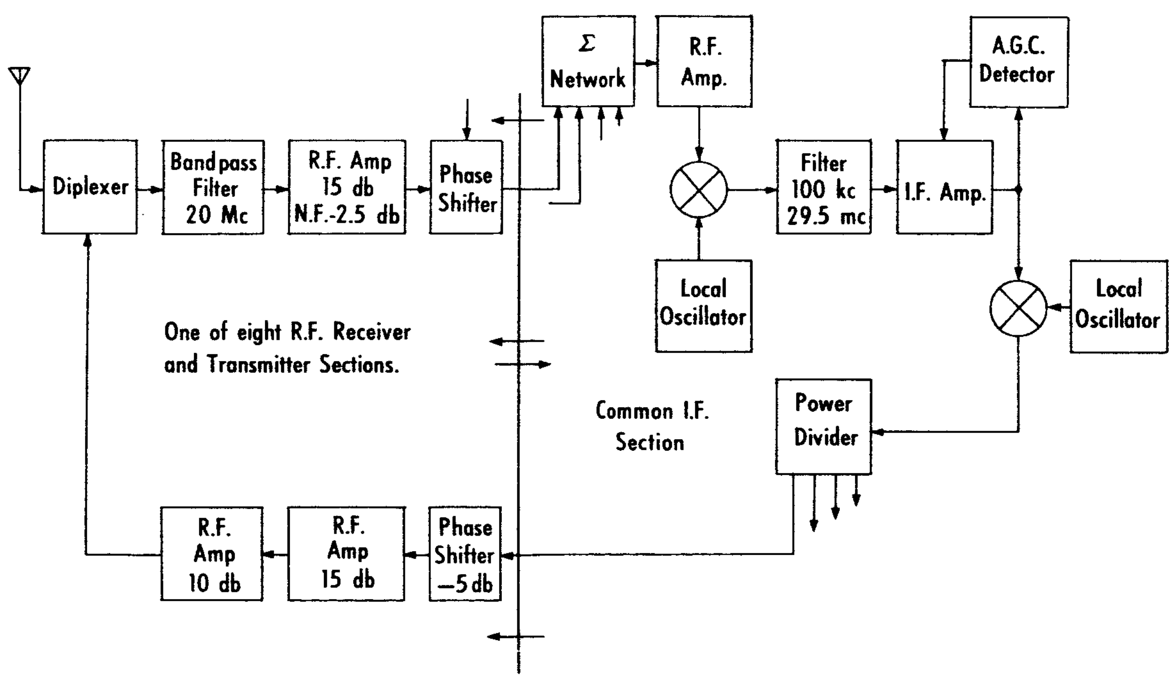


Figure 7—Satellite Transponder Functional Diagram

Table 4

Transponder Characteristics.

Transmitter power output (per whip)	7 dbw (5 watts)
Total power output	13.9 dbw (24.5 watts)
Transmitter antenna gain	8.5 db (approximately)
Transmitter losses (diplexers, cables, etc.)	1.5 db
Effective radiated power	23.6 dbw (230 watts)
Receiver noise figure	2.5 db
Receiver bandwidth	100 kc
Receiving antenna gain	8.5 db (approximately)
Weight	10.8 pounds
Power required	78 watts

received spectral density by at least 10 to 1. This will assure that the signal-to-noise ratio established at the platform will not be materially degraded by the satellite, and will allow the ground equipment to take full advantage of the bandwidth reduction improvement. Table 2 shows that the output power from the transponder of approximately one watt per 2 kc channel will be sufficient to assure reliable signal processing. This transponder will also be used to relay interrogation commands from the ground station to the platforms and the right-hand column of Table 2 indicates the wide margins available from the transponder in this mode of operation.

Platform-to-Satellite Transmission Link. The limiting portion of the overall platform-to-processing communication link will be the platform-to-satellite path even though the satellite-to-platform path results in a lower received signal-to-noise ratio. The lower signal-to-noise ratio in the later path will not be a limiting factor since it is used only for interrogation and redundant coding will be used. The primary requirement of the platform-to-satellite link is that the added noise be insignificant compared with that already present at the VLF receiver output. The VLF receiver worst case output will consist of a number of discrete or quasi-discrete tones whose total power will be small compared with the total noise power across the 2 kc band. That is, the worst-case received signal-to-noise ratio will be below zero db. The Omega tones will then only be discernible and useful after extraction by narrowband tracking filters at

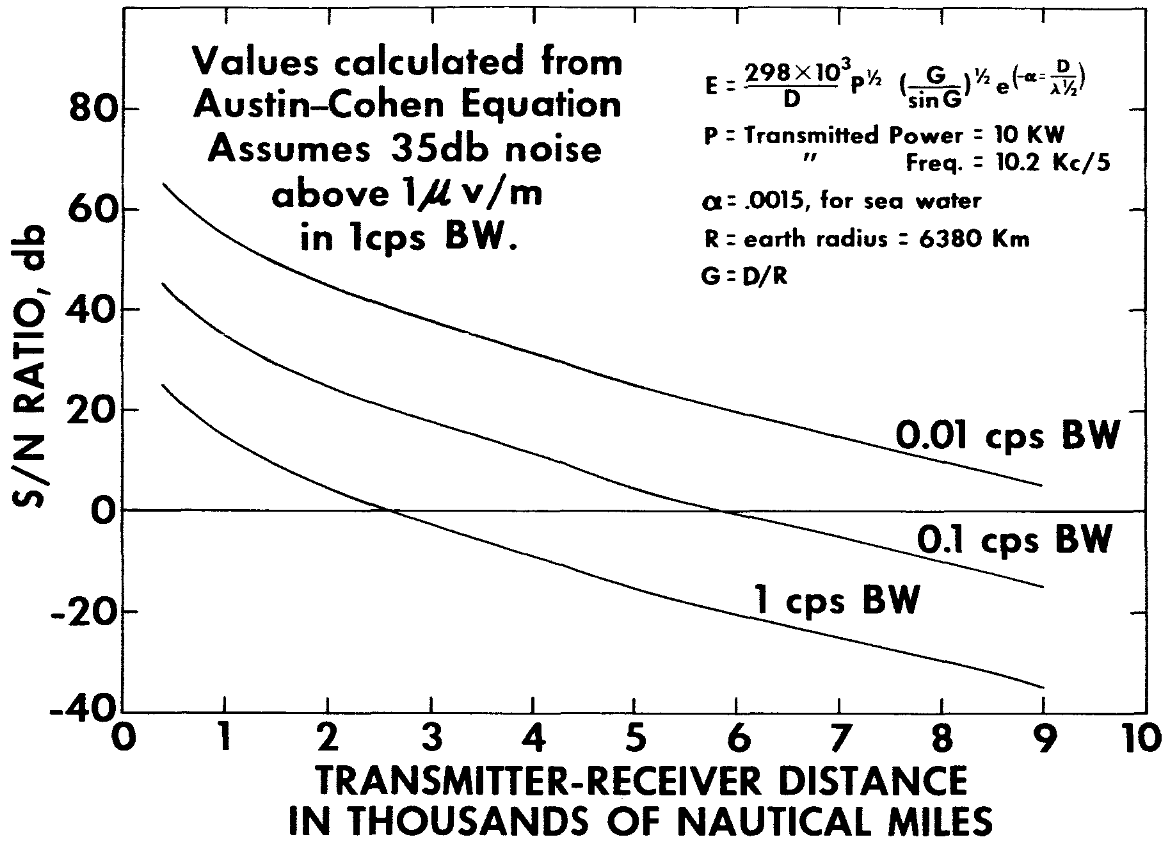


Figure 8—S/N Ratio vs Transmitter-Receiver Distance (D) for 10.2 kc

the data receiving center. Figures 8 and 9 show anticipated signal-to-noise ratios versus receiver-transmitter distances. Figure 8 is an approximate lower bound whereas Figure 9 is an approximate upper bound on an experimentally determined range of values (references (5) and (6)).

A reasonably accurate model of the signal transmitted from the platform is a uniform density or flat-white-noise signal. The ultimate phase measurements will not be materially altered by the addition of noise with a similar density distribution and with a total noise power of ten-to-one or less than that already present. Thus, a platform-to-satellite transmission link which can produce a 10 db minimum received signal-to-noise ratio over a 2 kc bandwidth will suffice. The amplitude linearity requirement of the communication link is not critical and a few percent of total harmonic and intermodulation distortion should be easily tolerated.

As with any time measuring scheme, uncontrolled phase distortion can produce large errors; however, with the system proposed here, serious problems

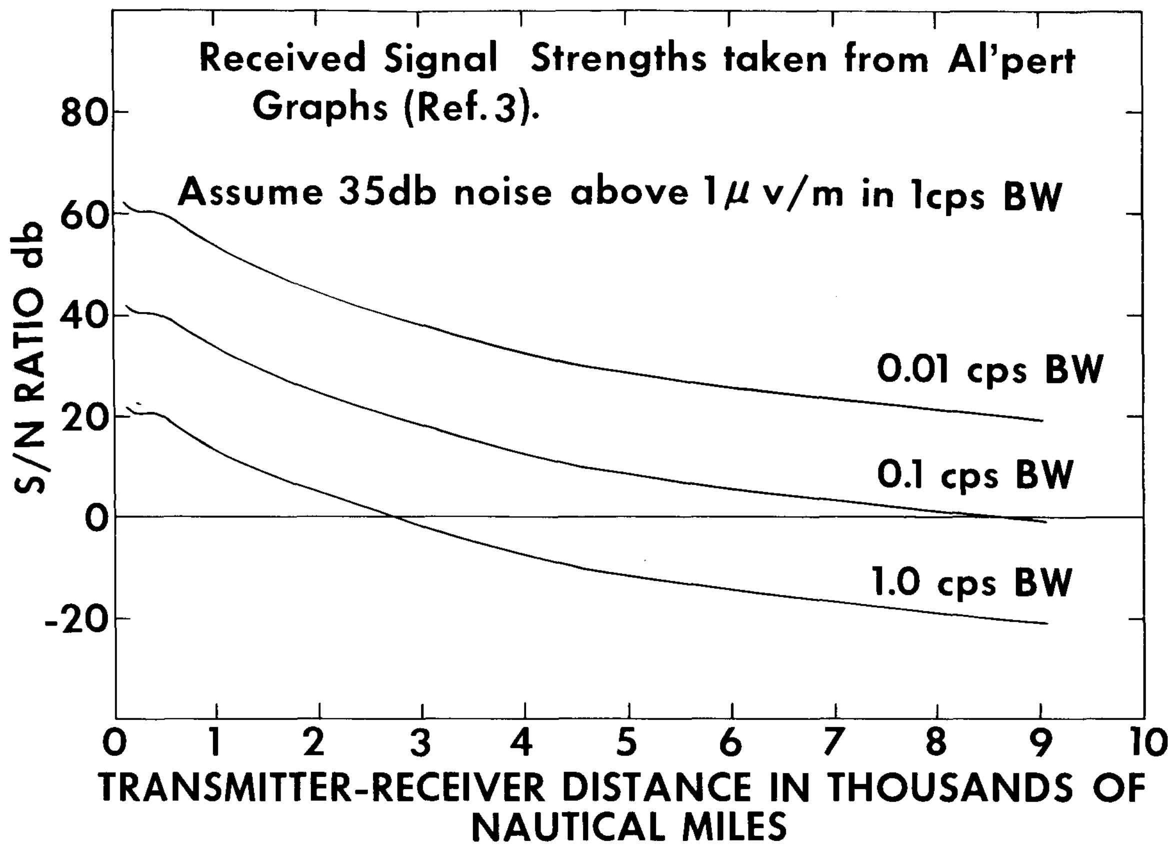


Figure 9—S/N Ratio vs Transmitter-Receiver Distance for 10.2 kc

should not exist. First of all, a reference tone will be laid on with the received Omega signals at the platform, which will be carried along to the processing equipment. This tone will allow for conversion oscillator instabilities and doppler effects. In addition, up to five microseconds of group delay distortion is permissible by virtue of the finest resolution distance of one-half mile. The Goddard Range and Range-Rate System, which uses a similar side-tone ranging technique, is evidence that the VHF propagation mechanism is capable of supporting much closer group delay requirements than this. As a result, the limitation should rest with equipment design and should be easily achievable.

5.2 Platform Interrogation

For ease in deploying and operating the experimental platforms, satellite interrogation techniques will be employed. The OPLE and IRLS interrogation requirements are considerably different and the interrogation scheme described below was devised as best suited to the OPLE system. However, further studies will be made of the two systems to determine the extent of compatibility that can be achieved. The ground station will emit an interrogation signal in the 148 Mc band at the proper frequency for the platform being interrogated. The satellite will relay the interrogation signal to the platform. Some degree of protection against false interrogation is desirable since an unrequested response from a platform can be disturbing to the system and response to alien transmissions is most undesirable. For this reason, each interrogation sequence will include the transmission of a particular platform address followed by a bit-by-bit inverse of the same address. The platform will perform bit-by-bit comparison in real time of the second received address with the first received address. In this way, single bit error rejection can be insured with a storage register of only half the length of the full interrogation sequence.

A six bit platform address would be sufficient for all of the platforms which would share a common transponding frequency in a 2000 platform per satellite operational system. That is, a six bit address would permit 64 unique platform addresses per transponder channel whereas only 40 addresses would be required with 50 transponder channels to service 2000 platforms. Assuming that the single-bit error probability is of some value, say Pe for each platform, the probability that a platform other than the one addressed will respond can be approximated by the value of $1/6\ Pe^{10} \cdot (1-Pe)^2$. Using a single-bit error probability of one per thousand, the above value becomes 0.17×10^{-6} or approximately two times out of ten million. On the other hand, the probability that the correct platform will successfully recognize its address can be found from the value of $(1-Pe)^{12}$ which for the same Pe is approximately 0.99 or about 99 times out of one hundred. This value could be increased by using more than two consecutive address transmissions with a "majority vote" logic on the platform. However, this additional circuitry does not seem warranted since the platform control center will have immediate knowledge of a failure to respond and can re-initiate the interrogation.

5.3 Platform Deployment

The ATS-C Command and Data Acquisition (CDA) Station will be at Rosman, N. C. and the received experimental data will be relayed over the existing data link to the Interrogation and Data Collection (IDC) Center at the Goddard Space Flight Center for processing and evaluation. The IDC Center will initiate all interrogation commands and transmit them to Rosman over the existing Command/Control link. It will also monitor the overall progress of the experiments as well as the performance of each of the deployed platforms. The IDC Center will continuously monitor the Omega network to determine its state of operation and to provide timing information for the platform processing equipment.

Twelve platform equipments will be fabricated and deployed for the ATS-C Experiment. Three platforms will be used to simulate balloon flights using aircraft. These air-borne platforms will provide information as to the optimum frequency of interrogations and reporting times required to minimize the platform power consumption without degrading the wind velocity determinations as measured by averaging the balloon tracks. These platforms will also be used in a separate experiment especially designed to evaluate the performance of a differential or relative location network for tracking balloons in the neighborhood of a fixed monitoring location.

Three platforms will be placed on NASA/GSFC tracking ships to provide Omega location information over a wide area for long periods of time and to compare the Omega positional information with the ships navigation aids. Two platforms will be placed on ocean buoys if possible to provide a long-term free-drifting environment which will augment the limited airborne tests. Two platforms may be placed on aircraft in conjunction with communications experiments using the ATS-C transponder and to evaluate the performance of the system with high speed aircraft. The remaining four platforms will be placed at widely placed fixed sites to provide an experimental standard. These receivers will be used in a differential Omega system test which will enable the moving platforms to be located to within a few hundred feet and to enable wind velocity measurements to within a few knots (reference (3)). At least one experiment will be performed with a van mounted receiver to evaluate performance on land. In order to closely control these activities, and to obtain real time information as to the operational status of each of the experimental platforms, a two-way voice service channel will be implemented through the transponder from the platforms to the control center.

6. FUTURE EXTENSIONS

One of the prime components of the proposed experiment, and of any future system, is the satellite antenna. At synchronous altitude, the angle subtended by the earth is 16.4 degrees. This would allow use of an antenna with approximately 20.1 db gain which would, assuming zero pointing error, provide a minimum of 17.1 db of gain over the entire illuminated area of the earth. An antenna pointing error of 25% (4.1 degrees) would necessitate using an antenna with a gain of 16 db gain, which would provide a minimum gain of 13.7 db over the illuminated area of the earth. Thus, the maximum allowable antenna gain is determined by the antenna pointing error, and since 4 degrees of error is well within the capability of present mechanical and electrical stabilization systems, a nominal 14 db gain antenna is easily feasible for an operational system. Table 3 shows the required nominal transmitter powers required for two hypothetical operational systems based on 14 db gain satellite antennas.

Once the feasibility of the OPLE concept is demonstrated by the proposed experiment, it will be possible to design an operational data collection and location system capable of serving a wide variety of users on a global scale. One possible additional technique compatible with the OPLE System would be the use of an automatic Omega receiver on the vehicles of users which have the space and power available. This receiver would reduce the Omega positional information to something on the order of 26 bits, thus greatly reducing the transmission power and/or transmission time required. A semi-automatic receiver currently being produced by the ITT Company for the U. S. Navy has 1 cubic foot of volume, weighs 45 pounds and requires 150 watts of primary power. This receiver contains cathode ray displays, electronic readout displays, battery pack and other auxiliary equipment not essential to automatic operation. Figures 10 and 11 are conceptual block diagrams of two Omega receivers in which microelectronic circuitry could be extensively used.

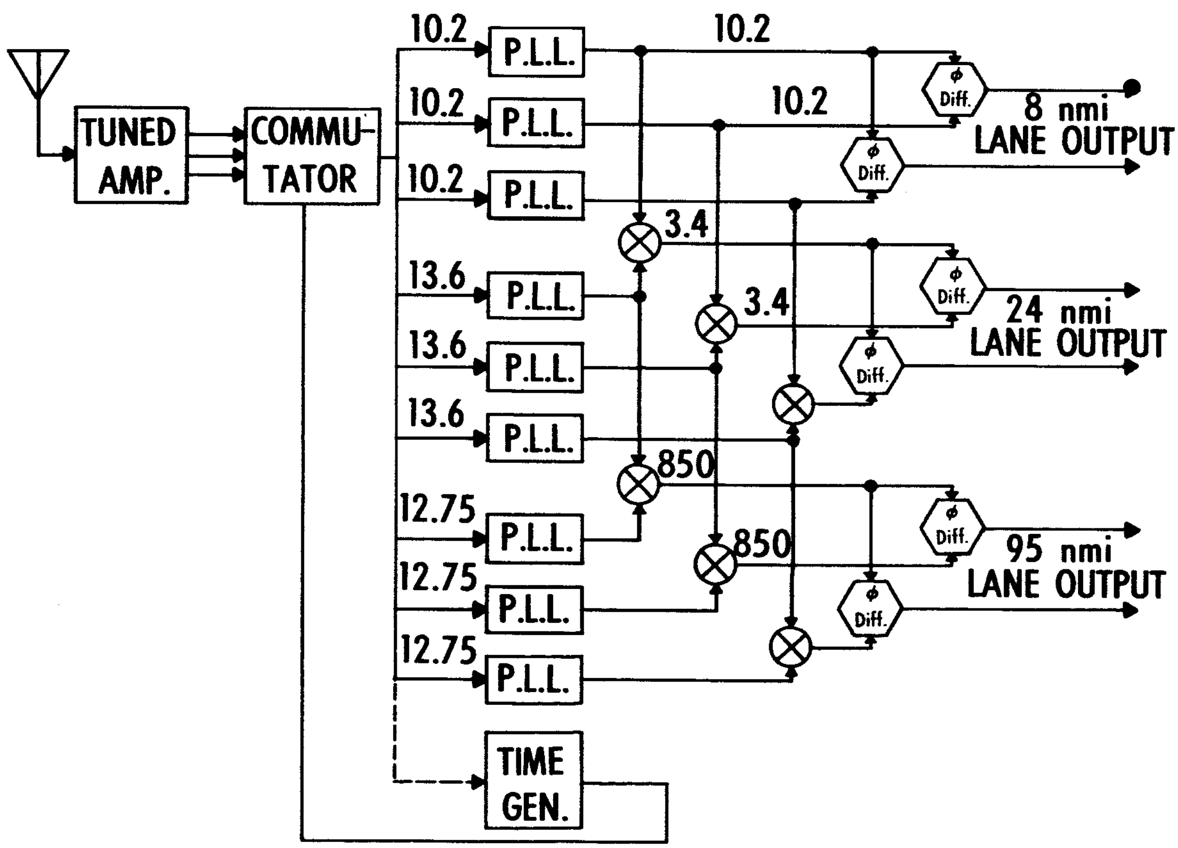


Figure 10—Functional Diagram of Conventional Omega Receiver

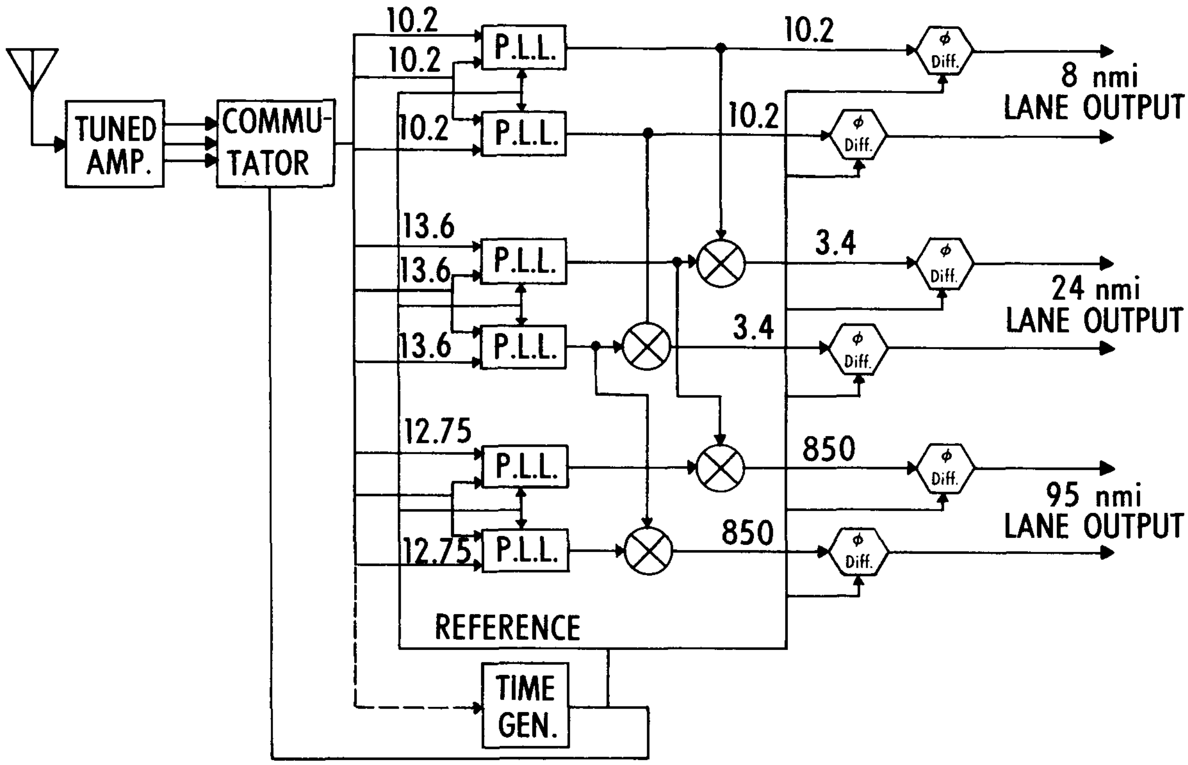


Figure 11—Functional diagram illustrating dual-input, phase-locked tracking filter approach

Using these concepts as a basis, commercial aircraft, including the Super Sonic Transport (see Appendix A), could be tied together in an air traffic control system capable of safely directing the anticipated air traffic for many decades to come. Also flight schedules and terminal traffic would be better controlled if timely knowledge was available as to exact arrival times. Steamship lines could also use this system for scheduling arrival times and port facilities to more economically operate and regulate their overall traffic.

Another possible application is as a recovery aid for the Apollo re-entry vehicle. With OPLE type equipment aboard the Apollo re-entry vehicle and the various units of the recovery force including the helicopters, it would be possible for a central control center to know the relative position of all the recovery units and spacecraft to within 200 yards and the absolute position of any one of them to within 1 or 2 miles regardless of the landing site location.

Meteorologists would have a means of gaining atmospheric and surface data by means of balloons and bouys. In the case of tethered bouys, the Omega portion of the receiver could be off with only the data channel activated for power conservation and in the event of a broken tether, the Omega receiver could be activated thus giving the position of the wayward bouy to service vessels. Oceanographers desiring ocean current and sea state data could use the system in much the same way. Also Zoologists desiring to ascertain the migration route of various land and air-breathing sea animals could possibly use such a system (reference (7)).

One control center operating the entire system would greatly increase the economy of the system as related to each individual user. Anyone desiring to use the system would inform the center of the intended region of operation, the platform frequency, and the number and time of the interrogations. The retrieved data and locations could then be sent to the user on a near real time basis or be provided in a more leisurely manner depending on the users requirements. An unmanned platform could thus be tracked for scientific data and a manned conveyance would be tracked for safety control and scheduling purposes and in addition have a voice and communications channel to a central control center. It would then be possible to learn more concerning the global phenomena of the earth and for the higher speed and more complex transportation systems to be run in a safer and more efficient manner.

7. MANAGEMENT

The Goddard Space Flight Center of the National Aeronautics and Space Administration will conduct the scientific investigation of the Omega Meteorological Platform Location and Data Collection Experiment and will produce the necessary equipments to demonstrate operational feasibility.

Responsibility for the investigation is assigned to the Systems Engineering Branch of the Systems Division, Goddard Space Flight Center. Dr. R. A. Stampfl is Chief of the Division and Mr. Moe I. Schneebaum is Head of the Systems Engineering Branch.

Contractors will be utilized to develop and fabricate the various equipments necessary for the experiment. Administrative support will be provided through Dr. Michael J. Vaccaro, Assistant Director, Office of Administration.

The Principal Investigator will be Mr. Charles Laughlin, Leader of the Omega Systems group in the Systems Engineering Branch. He will be responsible for defining the overall goals of the experiment and coordinating the efforts of the various groups during the experiment to assure realization of the initial goals. He will be responsible for establishing a working relationship with the Omega Project Office.

The co-investigator will be Mr. Gay E. Hilton, Systems Engineer in the Systems Engineering Branch. He will be responsible for the specification and implementation of the various equipments to be built by the contractors. He will also monitor the deployment of the various experimental platforms to assure a maximum usefulness of the acquired data.

Mr. Roger Hollenbaugh will coordinate the various efforts at GSFC and will be responsible for establishing an efficient data collection analysis and implementation system. In addition, he will function as the coordinator between the OPLE experiment and the IRLS experiment. He will also be responsible for integration of various equipments necessary to the experiment and he will assist in evaluating proposals, contractors' performance and overall progress of the experiment.

8. SCHEDULE

A.	Conceptual studies and preparation of specifications complete.	Dec. 1965
B.	Award of contract for satellite, launch support, and simulation equipment and service.	Mar. 1966
C.	Award of contract for platform equipment.	Jun. 1966
D.	Award of contract for ground station equipment.	Jun. 1966
E.	Delivery of satellite prototype and bench test equipment to satellite integration contractor.	Aug. 1966
F.	Award of contract for system integration and operational support services.	Jul. 1966
G.	Delivery of satellite simulation equipment to systems integration contractor.	Sep. 1966
H.	Delivery of flight qualified satellite equipment and launch support equipment to satellite integration contractor.	Oct. 1966
I.	Delivery of platform engineering model to system integration contractor.	Nov. 1966
J.	Delivery of ground equipment to system integration contractor.	Nov. 1966

K.	Delivery of twelve operational platform equipments to system integration contractor.	Mar. 1967 to May 1967
L.	Delivery of ground equipment to GSFC.	May 1967
M.	Completion of system integration.	Jun. 1967
N.	Deployment of fixed platforms to selected sites.	Jul. 1967
O.	Deployment of non-fixed platforms by cooperating agencies.	Aug. 1967
P.	Data collection and analysis.	Sep. 1967
Q.	Summary Report	Nov. 1967

9. FUNDING

FUNDING	FY 66	FY 67	FY 68	FY 69	Totals
A. Satellite and Launch Support					
Equipment Engineering Transponder (Satellite Simulator)	20K	80K			100K
Prototype Transponder	10K	90K			100K
Flight Transponder	5K	100K	15K		120K
Bench Test Equipment (modification of existing equipment)		50K			50K
Launch Support Equipment (modification of existing equipment)		90K	65K		155K
Integration and Launch Services	5K	85K	30K		120K
B. Platform Equipment					
Development and Engineering Model	160K	100K	100K		360K
Twelve Operational Units		150K	100K		250K
C. Ground Station Equipment (3 sets)	50K	350K	350K		750K
D. System Integration and Field Support		280K	100K	100K	480K
Totals	250K	1375K	760K	100K	2485K

References

(1) "Omega, A World-Wide Navigational System," System Specification and Implementation. Prepared by the Omega Implementation Committee for the U. S. Navy Department, Bureau of Ships, and submitted through the Office of Naval Research. Published for the Committee by Pickard and Burns Electronics, 103 Fourth Avenue, Waltham 54, Massachusetts,

(2) "Omega Navigation Capability Based on Previous Monitoring and Present Prediction Ability," by E. R. Swanson, 5 June 1964. Navy Electronics Laboratory, San Diego, California Report 1226.

(3) "Rendezvous Accuracy of the Omega Navigation System," by J. W. Brogden, A. N. Duckworth and J. J. O'Neill, 17 Nov. 1964. Radio Division of Navy Research Laboratory, Washington, D. C. NRL Memorandum Report 1573.

(4) "A Meteorology Experiment Employing the Interrogation, Recording and Location System." A Proposal for the Nimbus B Meteorological Satellite by G. Hogan and J. Cressey.

(5) Al'pert, Ya. L., Radio Wave Propagation and the Ionosphere, pp. 256-258, Consultants Bureau Enterprises, Inc., 1963, Authorized translation from the Russian, USSR Academy of Sciences Press, Institute of Terrestial Magnetism, the Ionosphere, and Propagation of Radio Waves, 1960.

(6) "Electromagnetic Field Strength Measurements at 10.2 Kilocycles Per Second" by E. R. Swanson, 17 Sept. 1964. Navy Electronics Laboratory, San Diego, California Report 1239.

(7) "The Navigation of the Green Turtle" by Archie Carr. Scientific American May 1965 pp. 78-86.

Appendix A

Position and Velocity Determination on High-Speed Aircraft

I. Standard Omega Receiver Approach

The standard Omega receiver is directly applicable for use on high speed aircraft. The only differences between operation on a stationary or slowly moving platform (less than 180 knots) are (1) the measured phase difference could vary at a noticeable rate, and (2) aircraft maneuvers could cause acceleration effects which affect the capability of the phase lock loops to lock on to an incoming signal.

The following is the form of the received signal from station A as seen by a receiver aboard a high speed aircraft (assuming no acceleration effects).

$$S_A = -\left\{\cos\left[\left(W_0 + W_{dA}\right) t + \phi_A\right]\right\}$$

The W_{dA} term is the doppler frequency caused by the aircraft motion relative to the transmitting station A; W_0 is the transmission frequency of the Omega station; and ϕ_A is the phase angle determined by the initial location of the aircraft relative to the transmitting station.

The signal from station B will be of the same form and is given below:

$$S_B = \cos\left[\left(W_0 + W_{dB}\right) t + \phi_B\right]$$

Putting S_A and S_B into a phase detector we obtain an output of the form:

$$\phi\,\text{difference} = \left(W_{dA} - W_{dB}\right) t + \phi_A - \phi_B$$

At any instant of time the above function defines isophase hyperbolic contours one of which includes the receiver position. The only difference between this and a slowly moving platform is that the $W_{dA} - W_{dB}$ term for the slowly moving case is so small that a very long time is required before it causes a noticeable change in the ϕ difference term.

The velocity vector could be determined by (1) measuring the position change over a known time interval (and calculating, V average = Δ position/Δ time); by determining the slope of the phase detector output, or by measuring doppler shifts and calculating the velocity component magnitudes with the following formula (Derived in Part II of the appendix, Eq. #4).

$$|\bar{V}|_k = \text{VELOCITY COMPONENT TOWARD STATION } S_k$$

$$|\bar{V}|_k = 3600 \ f_{dk} \lambda$$

where f_{dk} = doppler shift of frequency relative to station S_k. λ = wavelength of ranging frequency.

Once the receiver coordinates and velocity components relative to two stations have been determined, the navigator can determine his velocity vector relative to the ground as follows:

$$\bar{V} = x' \bar{i} + y' \bar{j}$$

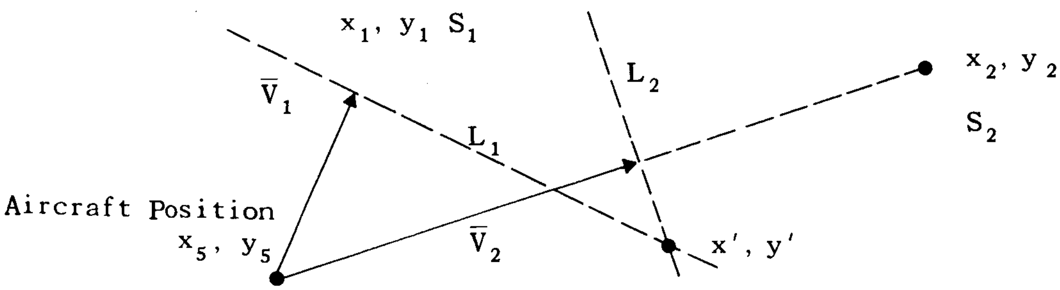
where

$$x' = \frac{V_1 \left(\frac{M_1}{y_1 - y_5}\right) - V_2 \left(\frac{M_2}{y_2 - y_5}\right)}{\frac{x_1 - x_5}{y_1 - y_5} - \frac{x_2 - x_5}{y_2 - y_5}}$$

$$y' = -\frac{x_2 - x_5}{y_2 - y_5} \left[\frac{\frac{V_1 M_1}{y_1 - y_5} - \frac{V_2 M_2}{y_2 - y_5}}{\frac{x_1 - x_5}{y_1 - y_5} - \frac{x_2 - x_5}{y_2 - y_5}} \right] + \frac{V_2}{M_2} \left[(y_2 - y_5) + \frac{(x_2 - x_5)^2}{(y_2 - y_5)} \right]$$

x' = magnitude of aircraft velocity parallel to equator
y' = magnitude of aircraft velocity perpendicular to equator

The above formulae are derived as follows:



S_1 = station 1
S_2 = station 2

$\overline{V}_1$ = velocity of aircraft toward S_1

$$\text{direction of } \overline{V}_1 = \frac{x_1 - x_5}{M_1}\,\bar{i} + \frac{y_1 - y_5}{M_1}\,\bar{j}$$

$\overline{V}_2$ = velocity of aircraft toward S_2

$$\text{direction of } \overline{V}_2 = \frac{x_2 - x_5}{M_2}\,\bar{i} + \frac{y_2 - y_5}{M_2}\,\bar{j}$$

Where

$$M_1 = \sqrt{(x_1 - x_5)^2 + (y_1 - y_5)^2}$$

$$M_2 = \sqrt{(x_2 - x_5)^2 + (y_2 - y_5)^2}$$

$$\overline{V}_1 = V_1\left[\frac{x_1 - x_5}{M_1}\,\bar{i} + \frac{y_1 - y_5}{M_1}\,\bar{j}\right]$$

Solving for equation of line L_1 (assuming origin located at X5, Y5) where L_1 is $\perp$ to $\overline{V}_1$ and passes through tip of $\overline{V}_1$.

$$L_1:\ y = -\frac{x_1 - x_5}{y_1 - y_5}\,x + b_1$$

$$V_1\,\frac{y_1 - y_5}{M_1} = -\frac{x_1 - x_5}{y_1 - y_5}\,V_1\,\frac{x_1 - x_5}{M_1} + b_1$$

$$b_1 = V_1\left[\frac{y_1 - y_5}{M_1} + \frac{(x_1 - x_5)^2}{M_1(y_1 - y_5)}\right]$$

$$L_1:\ y = -\frac{x_1 - x_5}{y_1 - y_5}\,x + V_1\left[\frac{y_1 - y_5}{M_1} + \frac{(x_1 - x_5)^2}{M_1(y_1 - y_5)}\right]$$

equation of line L_2:

$$L_2: y = -\frac{x_2 - x_5}{y_2 - y_5} x + V_2 \left[\frac{y_2 - y_5}{M_2} + \frac{(x_2 - x_5)^2}{M_2 (y_2 - y_5)} \right]$$

The vector from (X5, Y5) to the intersection of the two lines L_1 and L_2 is the velocity vector of the aircraft with respect to the ground.

$$x' = \frac{\dfrac{V_1 M_1}{y_1 - y_5} - \dfrac{V_2 M_2}{y_2 - y_5}}{\dfrac{x_1 - x_5}{y_1 - y_5} - \dfrac{x_2 - x_5}{y_2 - y_5}}$$

$$y' = \frac{x_2 - x_5}{y_2 - y_5} \left[\frac{\dfrac{V_1 M_1}{y_1 - y_5} - \dfrac{V_2 M_2}{y_2 - y_5}}{\dfrac{x_1 - x_5}{y_1 - y_5} - \dfrac{x_2 - x_5}{y_2 - y_5}} \right] + \frac{V_2 M_2}{y_2 - y_5}$$

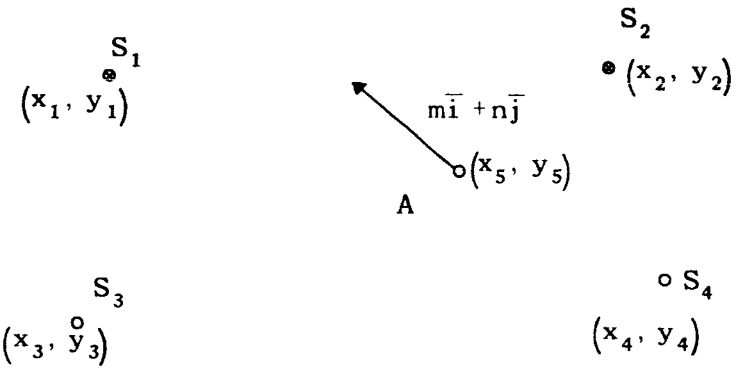
$$\overline{V} = x' \overline{i} + y' \overline{j}$$

The lane counting technique would be more applicable to high speed aircraft than the ambiguity resolution method using the sidetones. Flight time would be limited to several hours thereby decreasing the chance of losing a lane count that could occur on a ship which could require tracking for several days or an unmanned platform which could require tracking for several months. An aircraft would require almost continuous position and velocity information and less equipment would be required in the lane counting technique to achieve this.

For an aircraft velocity of 1800 knots perpendicular to the hyperbolic contours, a lane crossing would occur every sixteen (16) seconds (for an eight nautical mile wide lane). This rapid motion would require automatic operation with a minimum of functions for a navigator. At this velocity a temporary loss of signal could be critical. Therefore either other Omega tones would have to be utilized to check the lane count (by resolving the eight mile ambiguity) or external inputs would be necessary to periodically check and update the lane counter if necessary.

II. Direct computation of position and velocity vector from doppler frequencies:

The following scheme is based on the idea that the magnitude of the velocity of the receiver relative to each of four fixed transmitting stations uniquely determines both the position coordinates and the magnitude and direction of the velocity vector of the receiver.



The above diagram illustrates the problem. The aircraft is located at point A with coordinates (x_5, y_5) and the instantaneous velocity vector $m\bar{i} + n\bar{j}$. The unit direction vector from the aircraft (A) to each of the transmitting stations (s) is as follows:

$$A \rightarrow S_k : \frac{x_k - x_5}{M_k} \bar{i} + \frac{y_k - y_5}{M_k} \bar{j} \qquad \text{(EQ. \#1)}$$

where

$$k = 1, 2, 3, \text{ or } 4$$

and

$$M_k = \sqrt{(x_k - x_5)^2 + (y_k - y_5)^2}$$

The magnitude of aircraft velocity toward a particular station is found by taking the dot product of the velocity vector and the unit direction vector.

Velocity of aircraft toward station S_k :

$$|\bar{V}|_k = m\frac{(x_k - x_5)}{M_k} + n\frac{(y_k - y_5)}{M_k} \qquad \text{(EQ. \#2)}$$

With four stations there are four equations of the above form.

The values of X_k and Y_k are known since the transmitter sites are fixed.

The $|\bar{V}|_k$ quantities are calculated from the doppler frequencies as follows:

PHASE ϕ O ⟶ π IN RADIANS

DISTANCE D O — $\frac{\lambda}{2}$ IN NAUTICAL MILES

$$\phi = \frac{2\pi D}{\lambda}$$

For a moving platform

$$D_k = k|\bar{V}|_k\, t$$

therefore the ϕ due to the velocity is:

$$\phi_k = k\frac{2\pi|\bar{V}|_k\, t}{\lambda} \text{ radians}$$

Since $w = d\phi/dt$:

$$w_{dk} = k\frac{2\pi|\bar{V}|_k}{\lambda} \text{ radians/second}$$

$$w_{dk} = \frac{2\pi|\bar{V}|_k}{\lambda} \text{ radians/second}$$

this angular frequency = 2πx doppler frequency

$$\therefore f_{dk} = k\frac{|\bar{V}|_k}{\lambda} \qquad \text{(EQ. \#3)}$$

for λ in nautical miles, $|\bar{V}|_k$ in knots and f_d in cycles per second; a conversion factor (K) of 1 hour per 3600 seconds is required. Solving for $|\bar{V}|_k$

$$|\bar{V}|_k = 3600\, f_d\, k \text{ knots} \qquad \text{(EQ. \#4)}$$

where $f_d k$ is the frequency shift of the transmissions from station S_k as seen by the aircraft.

We are now left with four simultaneous equations and the four unknowns m, n, x5 and y5.

Solution of these equations will yield the instantaneous position coordinates and velocity vector.

Since we are concerned with the magnitude of the doppler frequency, which is directly proportional to the ranging frequency, it would be advantageous to use the highest frequencies to measure the doppler shift. For a velocity of 1800 knots, the following maximum doppler frequencies are obtained at 10.2 kc and 13.6 kc by using Equation #3.

10.2 kc → .03125 cps maximum

13.6 kc → .04167 cps maximum

A doppler frequency of 0.0003 cycles per second yields a value of approximately 17 knots, when a ranging frequency of 10.2 kc is used, as calculated by using Eq. #4. The frequency of the received signal containing this doppler frequency is 10200.0003 cps. This is a doppler frequency shift of 3 parts in 10^8 of the received signal.

Therefore, the ability to resolve velocity components to within 17 knots requires accuracies in the received signals (which are used to determine the doppler frequencies) of 3 parts in 10^8.

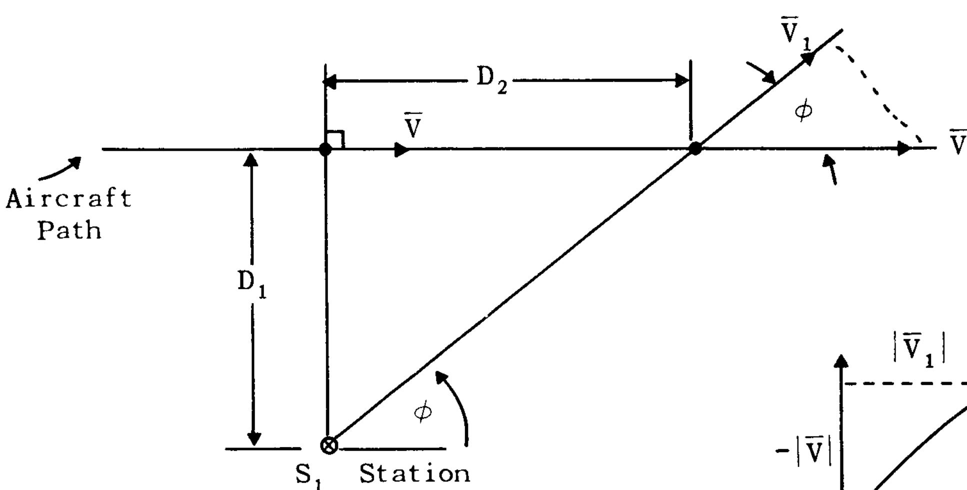
III. Acceleration Errors

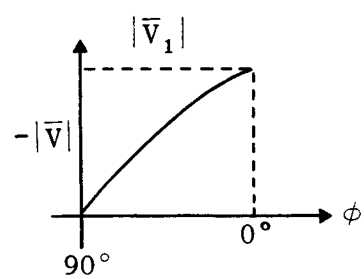
In each of the previously mentioned cases acceleration effects due to changes in the velocity components of the aircraft relative to the transmitting stations will cause errors in position and velocity measurements. This is caused by the inability of second order loops to precisely track acceleration effects. In second order, type 1 loops an acceleration step input is tracked with a constant error. This would result in position and velocity errors.

There are two separate causes of acceleration for the case of a velocity vector with a constant magnitude.

(1) Consider the aircraft velocity vector with a constant direction. For this case the relative velocity vector with respect to each transmitting station changes continuously. This effect causes an acceleration input to the measuring circuitry. The acceleration for this case is calculated as follows:

Rate of change of frequency due to maximum radial acceleration.





GRAPH A

Graph A shows relationship between aircraft position with respect to Station S_1, and aircraft velocity as viewed by the station:

$$|\bar{V}_1| = -|\bar{V}| \cos \phi$$

$$\frac{d|\bar{V}_1|}{dt} = |\bar{V}| \sin \phi \frac{d\phi}{dt}$$

$$\phi = \cot^{-1} D_2/D_1$$

$$D_2 = |\bar{V}| t$$

$$\phi = \cot^{-1} \frac{|\bar{V}| t}{D_1}$$

$$\frac{d\phi}{dt} = -\frac{1}{1 + \left(\frac{|\bar{V}| t}{D_1}\right)^2} \frac{|\bar{V}|}{D_1}$$

$$\sin \phi = \frac{D_1}{\sqrt{D_1^2 + D_2^2}} = \frac{1}{\sqrt{1 + \left(\frac{D_2}{D_1}\right)^2}}$$

$$\frac{d|\bar{V}_1|}{dt} = -|\bar{V}| \left[\frac{1}{\sqrt{1 + \left(\frac{|\bar{V}| t}{D_1}\right)^2}}\right] \frac{1}{1 + \left(\frac{|\bar{V}| t}{D}\right)^2} \frac{|\bar{V}|}{D_1}$$

$$\frac{d|\bar{V}_1|}{dt} = \frac{|\bar{V}|^2}{D_1} \frac{1}{\left[1 + \left(\frac{|\bar{V}| t}{D_1}\right)^2\right]^{3/2}}$$

when

$$t = \pm\infty, \quad \frac{d|\bar{V}_1|}{dt} = 0$$

when

$$t = 0, \frac{d|\bar{V}_1|}{dt} = -\frac{|\bar{V}|^2}{D_1} \text{ max. acceleration.}$$

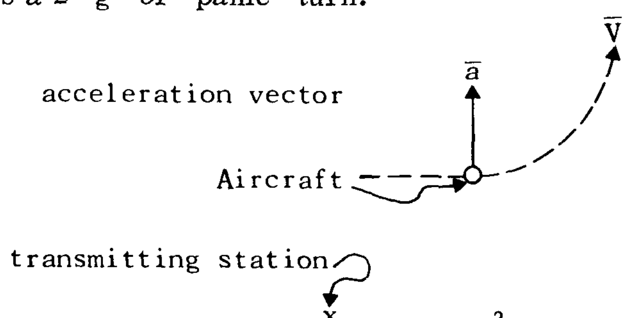
$$\frac{df}{dt} = \frac{|\bar{V}|}{D_1} \frac{(\text{n. mi/hr})^2}{\text{n mi}} \times \frac{1 \text{ cycle}}{16 \text{ n mi}} \times \frac{1(\text{hr})^2}{(3600)^2 (\text{sec})^2}$$

max. rate of change of frequency:

$$\frac{df}{dt} = 0.482 \times 10^{-8} \frac{V^2}{D} \text{ cycles/sec}^2$$

v = aircraft velocity (knots)
D = distance between transmitting station and line that velocity of aircraft lies on (nautical miles).

(2) Consider an aircraft velocity vector with a changing direction. This case is caused by aircraft maneuvers. The acceleration realized in this case can be several magnitude larger than that for case (1). The following analysis considers a 2 "g" or "panic" turn.



$$a = \frac{v^2}{R}$$

$$2 \times 32.2 \text{ f/sec.}^2 = 64.4 \text{ ft/sec}^2 \times \frac{(3600 \text{ sec})^2}{\text{hr}^2} \times \frac{1\text{mi}}{5280 \text{ ft}} \times \frac{\overset{\text{n.mi}}{0.87}}{1 \text{ mi}}$$

$$a = 13.78 \times 10^5 \frac{\text{nmi}}{\text{hr.}^2}$$

$$\text{radius of turn} = R = \frac{V^2}{13.78 \times 10^5 \text{ n.m.i.}}$$

$$\text{for velocity} = 1800 \text{ knots}; \; R = 2.35 \text{ n.m.i.}$$

$$\frac{df}{dt} = .0106 \frac{\text{n.mi}}{\text{sec.}2} \times \frac{1 \text{ cycle}}{16 \text{ n.m.}} = 6.63 \times 10^{-4} \text{ cycle/sec}^2$$

It might be necessary to provide inputs from equipment external to the Omega receiver to eliminate this effect.

Comparison of the two methods

The method of utilizing the Omega transmission that is described in Part I of the Appendix has several advantages over the second method. The first method requires the reception of signals only from three (3) transmitting stations while the second method requires four (4) signals. The standard receiver can be used when the aircraft is on the ground and also to achieve the high rendezvous accuracies while the doppler dependent system would be useless in both these cases.

One advantage of the doppler system is that it allows unique position determination without the ambiguities of the standard receiver. Therefore a loss of signal is important only during that time interval when the signal is not present and does not introduce a continuous error that has to be corrected. In addition only one ranging frequency is required therefore eliminating the need to process other frequencies.

Neither method has advantages over the other in eliminating errors due to accelerations since both require the phase lock tracking filters to recover the signals from noise before processing.

The doppler system eliminates errors introduced by the divergence of the hyperbolic contours since it does not make measurements on differences of received signals from different stations but makes measurements on each signal separately and therefore is essentially a circular system.

The preceding analysis is performed on a planar surface. The results prove the feasibility of the methods; however, they would have to be extended to a spherical surface to allow their use in converting the Omega signals to parameters in terms of longitude and latitude.

Appendix B

OPLE and IRLS Comparison

The Interrogation, Recording and Location System (IRLS) is a two-way (round trip) ranging system for locating responding platforms by means of an orbiting satellite. Two separate range measurements are made at different times during an orbit while a given platform remains in radio view of the satellite. The separate range measurements along with the orbit ephemeris permit a geometric solution of the platform position. The IRLS ranging pattern which modulates the UHF satellite-to-platform transmission frequency includes a 12.5 kc tone. The phase difference between the transmitted 12.5 kc tone and the delayed return from the platform serves as a measure of the two-way transit time or distance from the satellite to the platform. The precision of measurement of this phase difference determines the range resolution and the ultimate position location accuracy possible.

The Omega system is based on the same fundamental idea in that the phase difference between two 10.2 kc tones is measured to determine relative distances of the receiver from Omega transmitting stations and the ultimate accuracy again depends upon the precision of this measurement. In the case of Omega, the 10.2 kc tone is propagated directly via the VLF media without the need to modulate another carrier frequency. While this simplified discussion in no way substantiates the fact that the accuracy of the two systems is comparable, it does point out that the method of determining the least significant range unit is essentially the same.

Since the phase angle of a sinusoidal function is periodic, the measured phase difference in each of the systems is ambiguous. In the IRL System, this ambiguity is resolved by a coded wave train of square modulating pulses having a repetition period which is comparable to the longest possible transmission delay. This method requires a transmission bandwidth which is just not available at VLF frequencies. In the Omega system, a composite spectrum consisting of a multiplicity of continuous tones is transmitted such that the period of lowest difference tone is comparable to the longest possible transmission delay difference. The method of resolving the ambiguity is different in the two systems, but the fundamental operations are the same.

Nevertheless, certain features of the two systems are sufficiently different to make a meaningful comparison between them difficult to tabulate. However, an attempt to do so is given in Tables 1 and 2 below, which are based on the experimental systems that have been proposed. In particular, the use of a

TABLE 1

Comparison of OPLE and IRLS Experimental Characteristics

ITEM	OPLE	IRLS
1. Spacecraft	ATS-C	Nimbus B
a. Orbit	Equatorial (Sync. Alt.)	Polar (600 nm to 1500 nm)
b. Equipment	Linear VHF Transponder (no storage)	Special Subsystem (address,time and data storage)
2. Ground Facilities		
a. Command and Data Acquisition Stations	Rosman	Alaska
b. Data Link	Existing Real-time Relay Facilities	Existing Punched Tape Data Link
c. Address Link	Existing Real-time Relay Facilities	Existing Punched Tape Data Link
d. Address Method	Random Access	Stored Program Each Orbit
e. Other Ground Facilities	Active Omega Network Required	Self-contained
3. Platforms		
a. Size, Weight and Cost	Comparable	Comparable
b. Number Planned	12	12
c. Maximum Number Possible	2000 (each interrogated once/2 hrs)	20/orbit*
d. Data Collection Rate	Real Time	Up to 1 Orbit Delay
e. Performances at Maximum Balloon Velocities (100-200 Knots)	Good	Fair (requires careful programming)

• This limit, imposed on the first experiment, is due only to the size of the command and data memories which can readily be increased.

TABLE 2

Comparison of OPLE and IRLS Parameters

ITEM	OPLE	IRLS
1. Frequency Band	136/148 mc	401/466 mc
2. Bandwidth Required		
a. Spacecraft	100 kc	100 kc
b. Platform	2 kc	100 kc
3. Position Location Accuracy	±1.0 to ±2.0 n. miles	±1.5 n. miles
4. Platform Transmission Time	3 minutes max.	3.2 seconds
5. Platform Transmitter Power Output	5 watts (2W)*	25 watts
6. Platform Standby Average Power		
a. Timed Receiver	50 to 75 milliwatts	50 to 75 milliwatts
B. Continuous Operation	Approx. 0.5 watts	0.5 watts
7. Energy Dissipated/Interrogation	3600 watt-sec. (1440)*	750 watt-sec.
8. Energy Required for Six-months Lifetime		
a. Timed Receiver	684 watt-hrs.	399 watt-hrs.
b. Continuous Operation	2520 watt-hrs.	2235 watt-hrs.
9. Number of Data Bits	1000 to 2000 bits/sec.	1176 bits total/interrogation

* These values hold if an operational system uses the 401/466 mc band.

single synchronous satellite (ATS-C) is assumed in the case of OPLE and the use of a single 600 n. mile altitude polar orbiting satellite (Nimbus B) is assumed in the case of IRLS.

To appreciate the limitations of these tables, the salient differences between the two systems should be pointed out. The IRLS location scheme depends upon the geometry of an orbiting satellite and is thus not adaptable to use with synchronous satellites. As a result, the IRLS satellite must have an on-board storage for platform addressing which can be programmed for the sequence of activities of each orbit. Therefore, sufficient a-priori knowledge of platform locations must be available to permit accurate address programming. For collection of synoptic data, a system of orbiting satellites would be required to provide frequent enough interrogations.

The outstanding feature of the OPLE system is that all platforms in view of the synchronous satellite (which does not include all of the polar region) can be randomly addressed and located. A given platform can be interrogated as frequently or infrequently as desired. Thus, concentration can be focused on meteorologically significant areas with only occasional reporting from less active areas. Also, an ailing platform can be favored with less activity without danger of losing contact with it. The control center would have a panoramic view of all platform activity so that errant platforms could be shut off or missed interrogations could be repeated. Potentially, the system can be configured to provide tracking of platforms moving at any speed.

However, true global coverage with either system, or by a combination of the two systems, would require a minimum of three satellites and this is not reflected in the tables presented here. In particular, item 3c of Table 1 shows a maximum of twenty platforms for the IRLS system. It is stressed that this number is a result of parameters chosen for the first IRLS experiment and that in operational systems based on either OPLE or IRLS the total number of platforms that could be deployed would be comparable. This table also indicates that the size, weight and cost of the platforms should be comparable.

Table 2 shows that the total platform energy required for either system is also comparable although the numbers do differ by some amount when a timer is included to activate the interrogation receiver according to some schedule (item 8a). However, it should be pointed out that the maximum transmission time of three minutes was assumed for the OPLE system. In actual operation, the transmission length can be controlled at will by the control center and will usually run less than three minutes. In addition, timed operation with the IRL System is somewhat more difficult to schedule so that the total platform energy required for the same number of interrogations is comparable.